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(56) Documents Cited
EP 0743215 A **EP 0354790 A** **EP 0175952 A**
WO 97/08440 A **WO 97/08438 A** **WO 86/04747 A**
US 5185543 A

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(54) Abstract Title
Vehicle hybrid drive system and operating method

(57) A hybrid drive arrangement in which a motor vehicle is propelled simultaneously by an engine and an electrical machine. The electrical machine (2) is coupled directly with the internal combustion engine (1) and final drive (5), and operates alternately as a motor and generator which assists or retards respectively the internal combustion engine in a controlled cycle operation. Energy extracted during each power cycle of the internal combustion engine is conveyed either mechanically to the final drive or electrically to the electrical storage unit (4). Through this method of active power cycle averaging, energy distribution is managed for vehicle propulsion and replenishment of the electrical storage unit. The step-less combined output characteristics of the system enhances and modifies the performance of the internal combustion engine to provide high torque at low speeds, additional acceleration torque, and smoothing of torque pulses from the internal combustion engine.

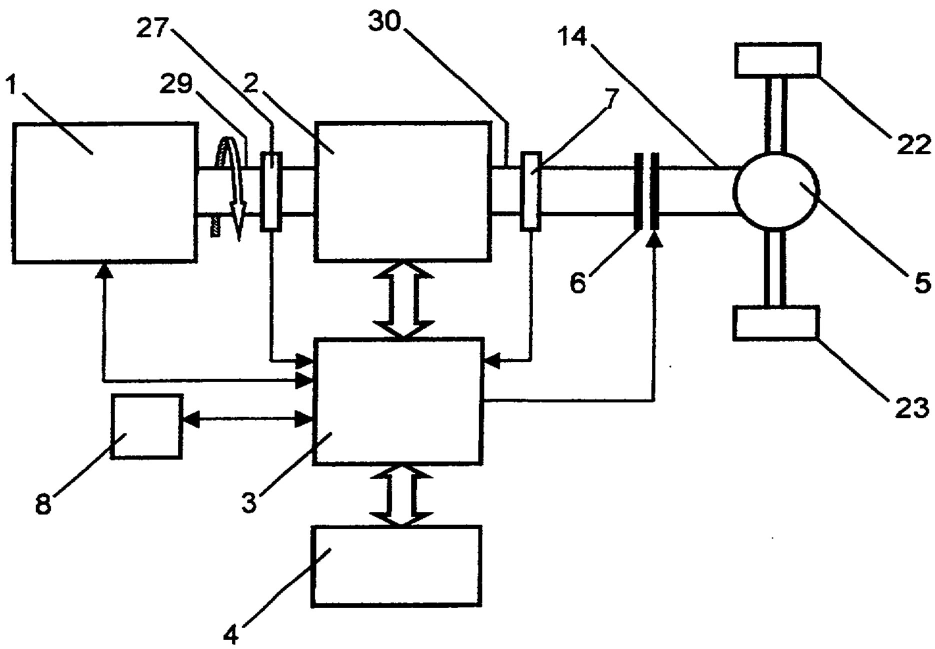

FIGURE 1

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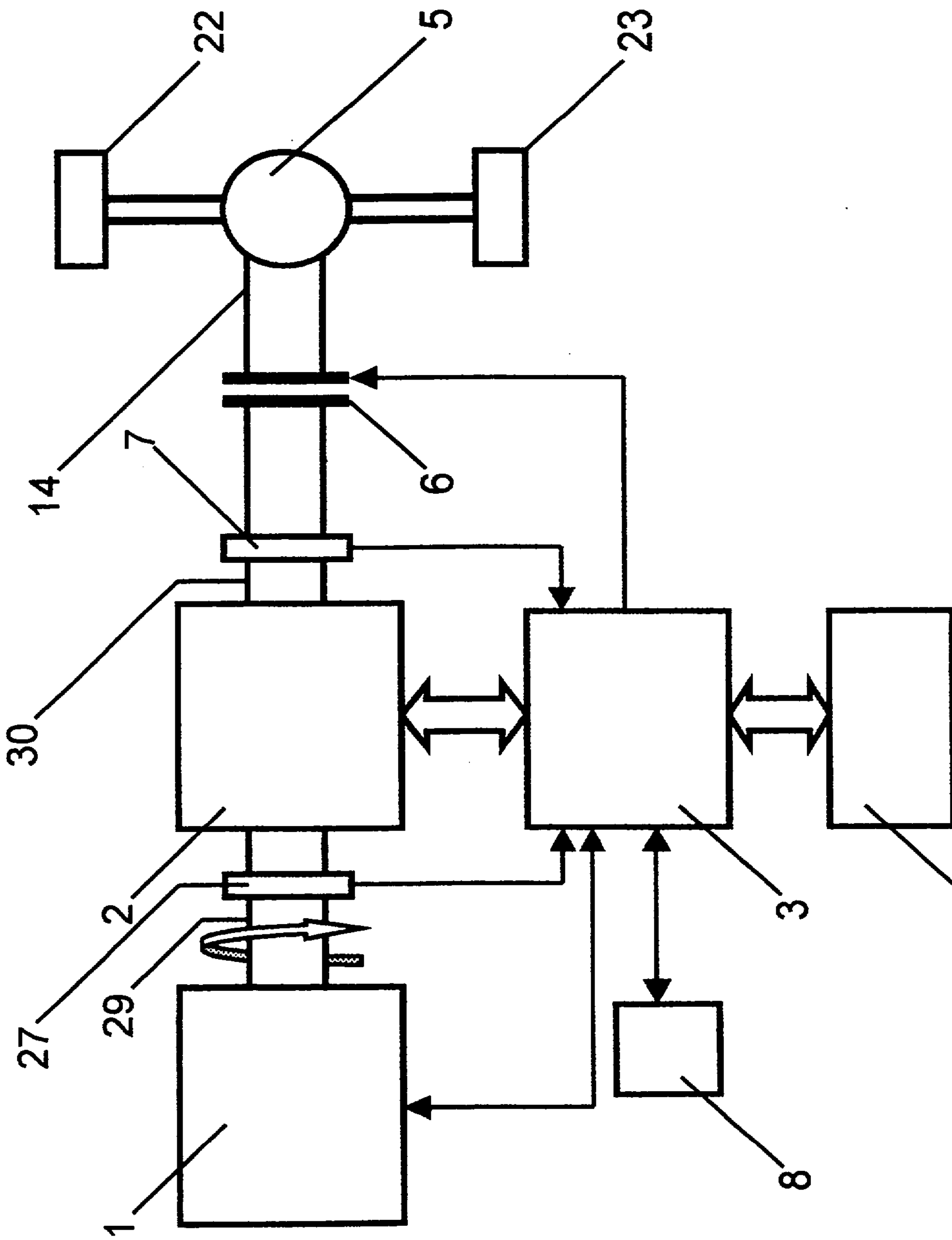

FIGURE 1

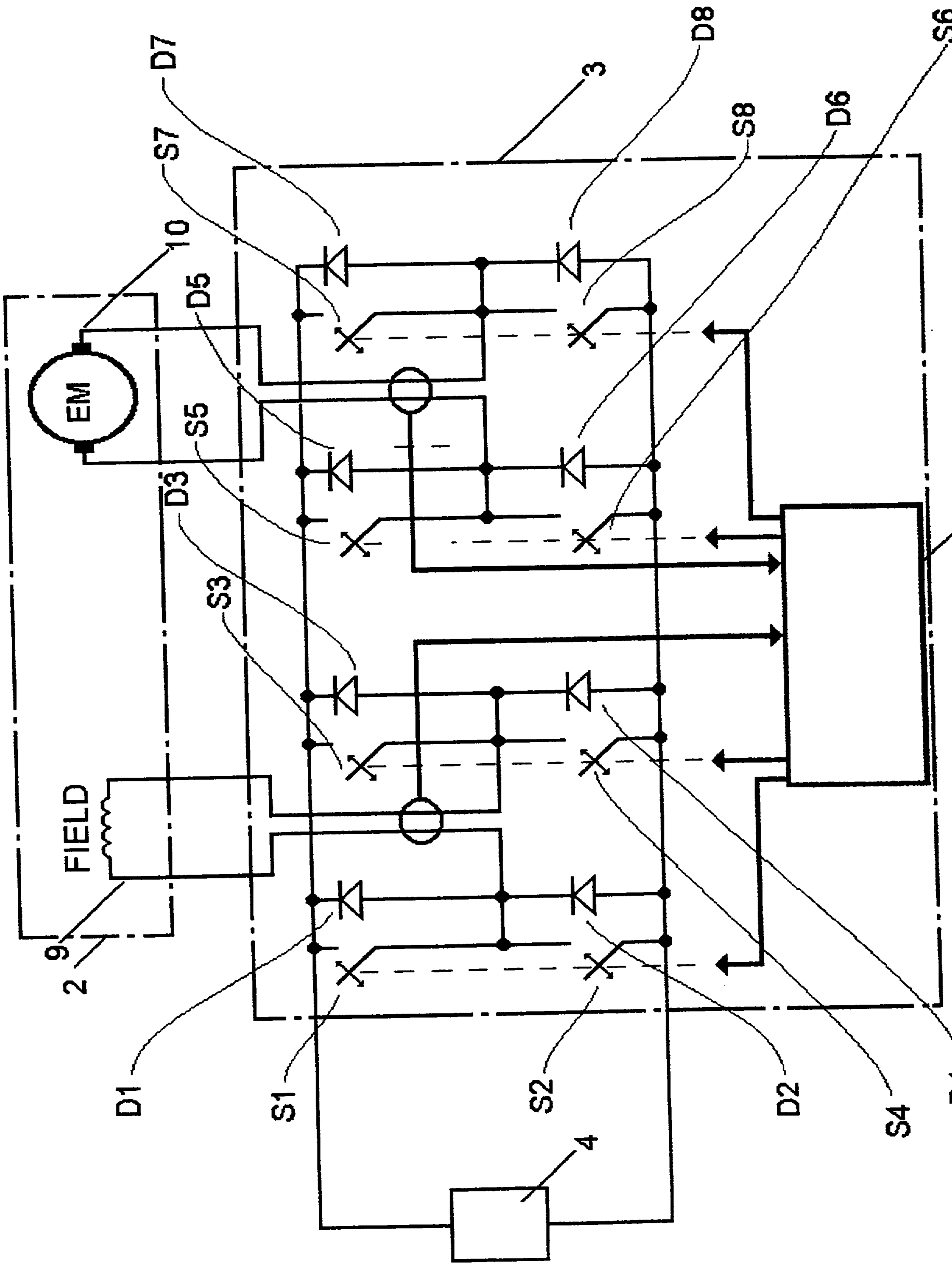

FIGURE 2

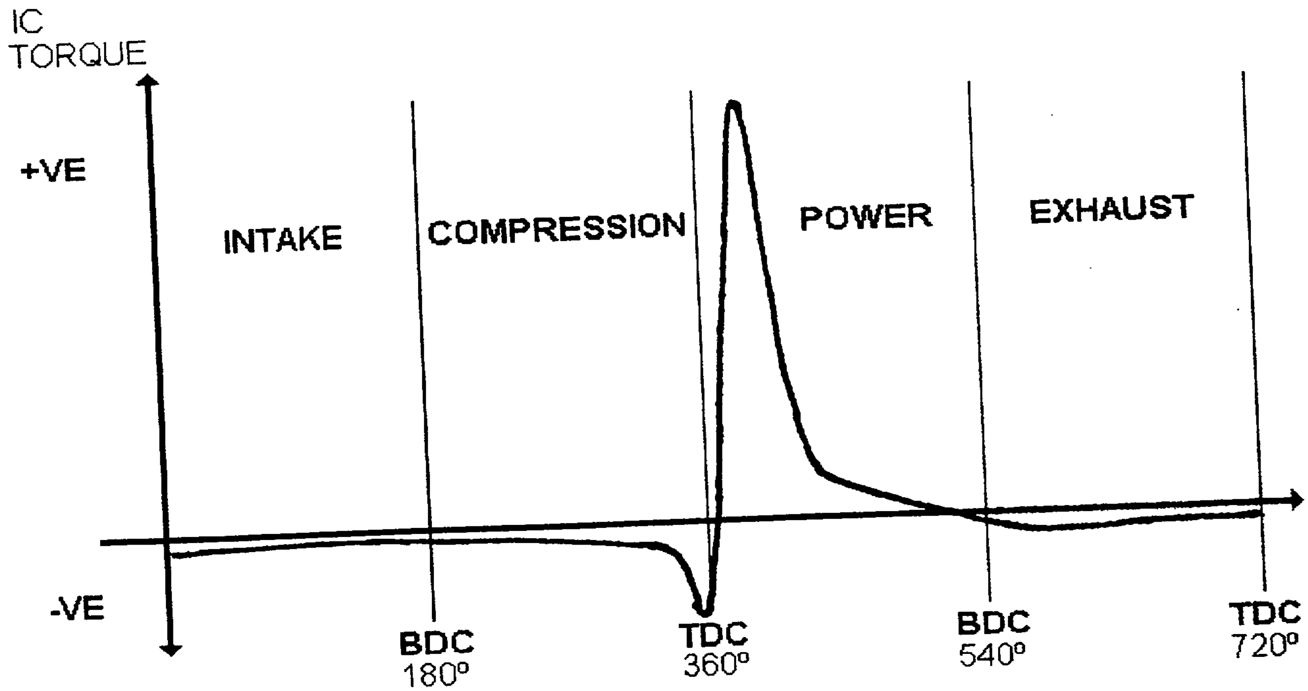

FIGURE 3

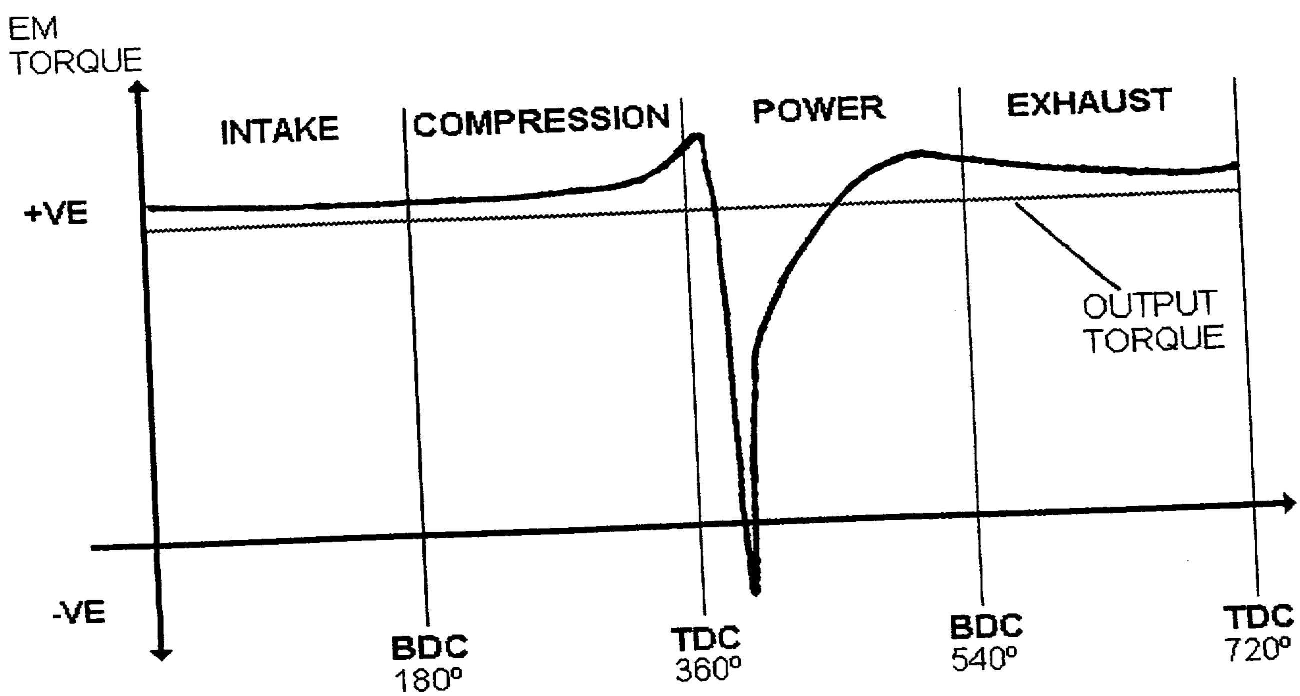

FIGURE 4

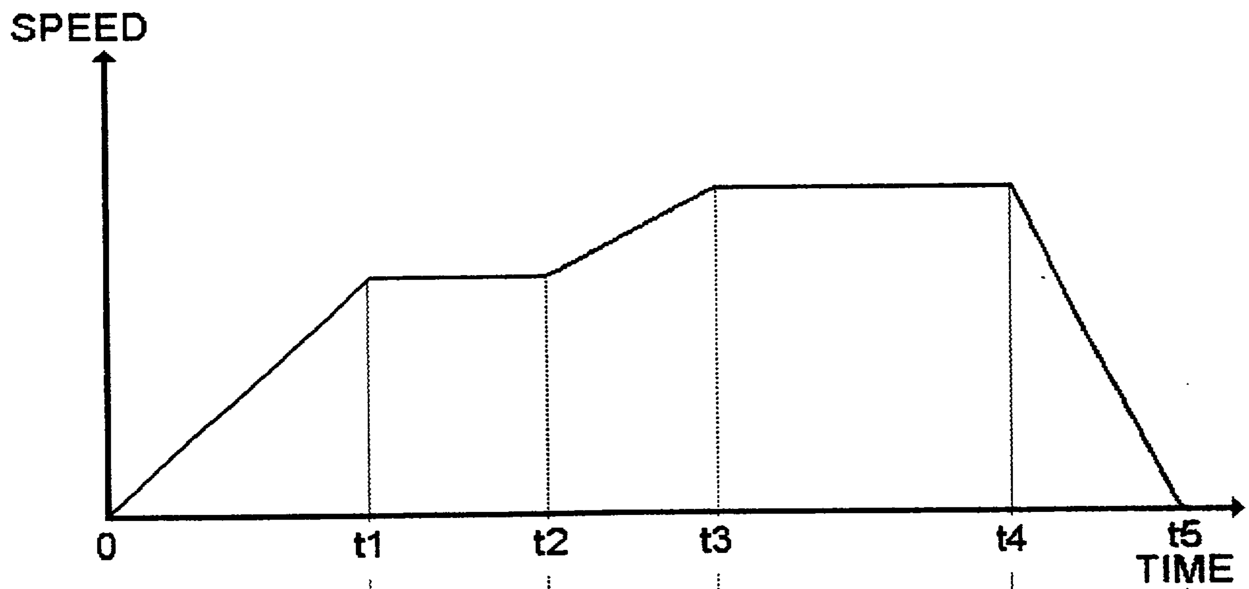

FIGURE 5

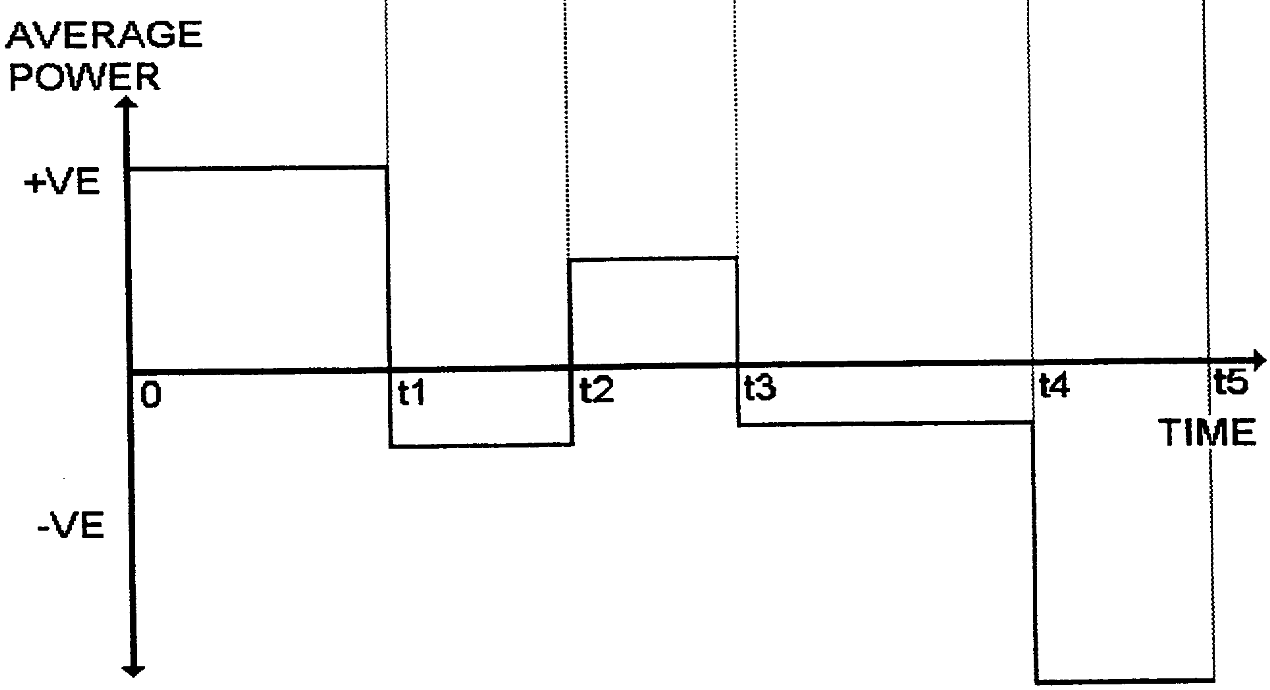

FIGURE 6

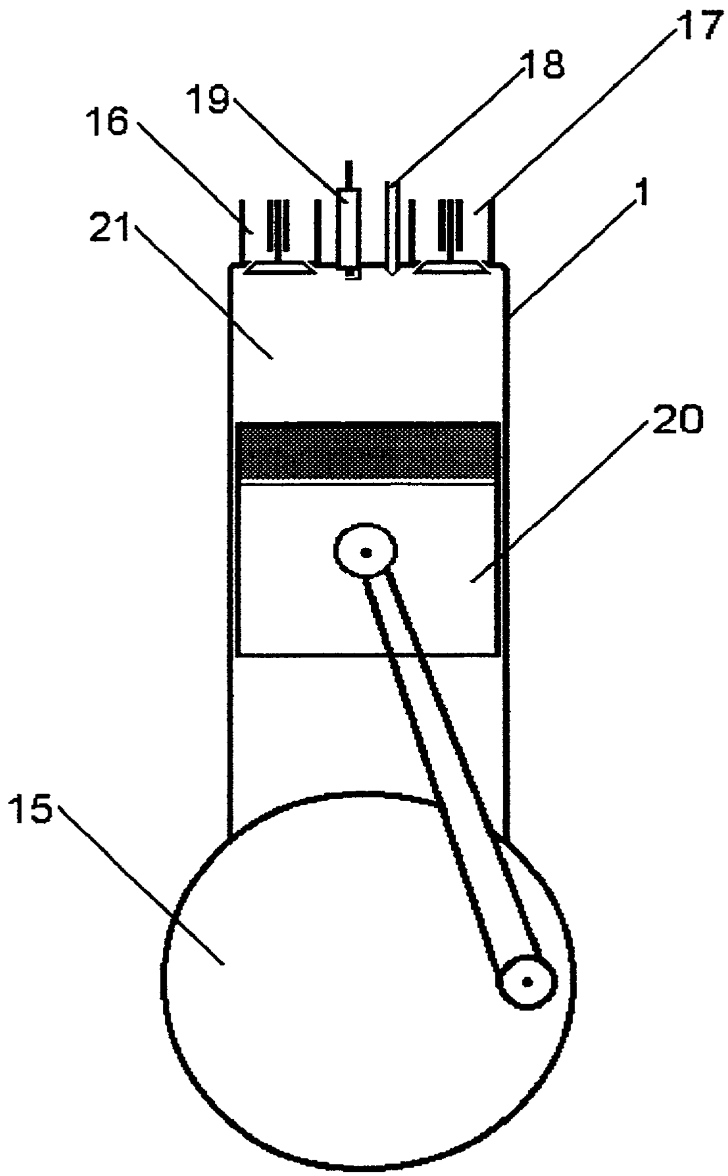

FIGURE 7

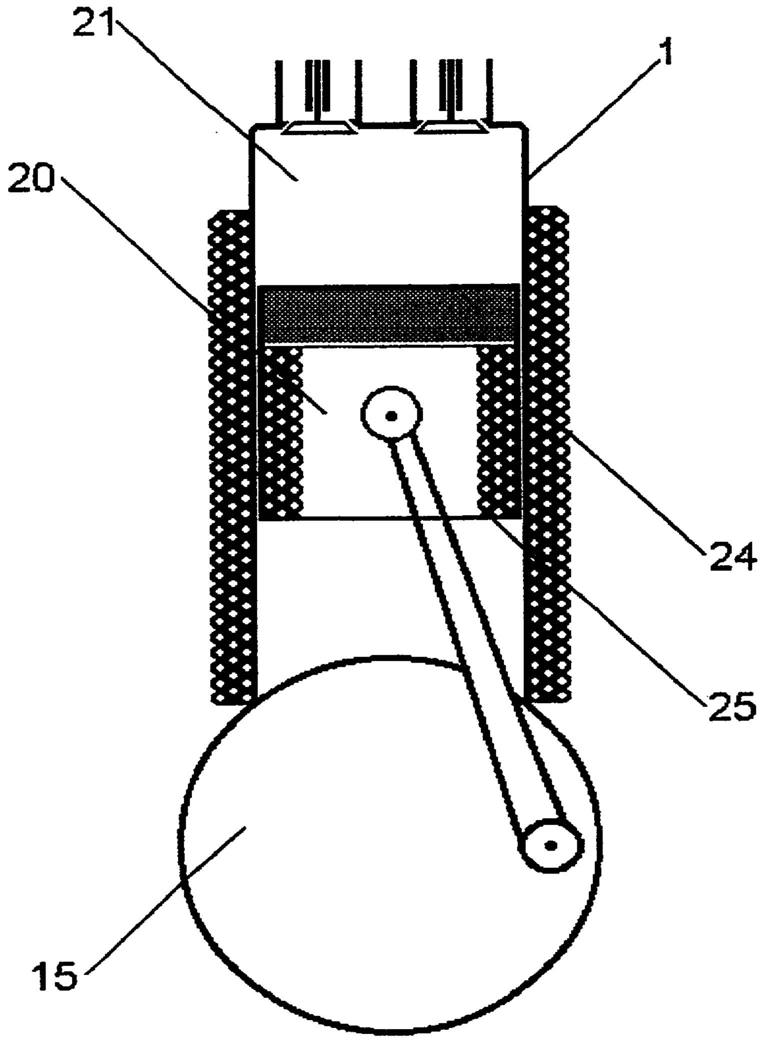

FIGURE 8

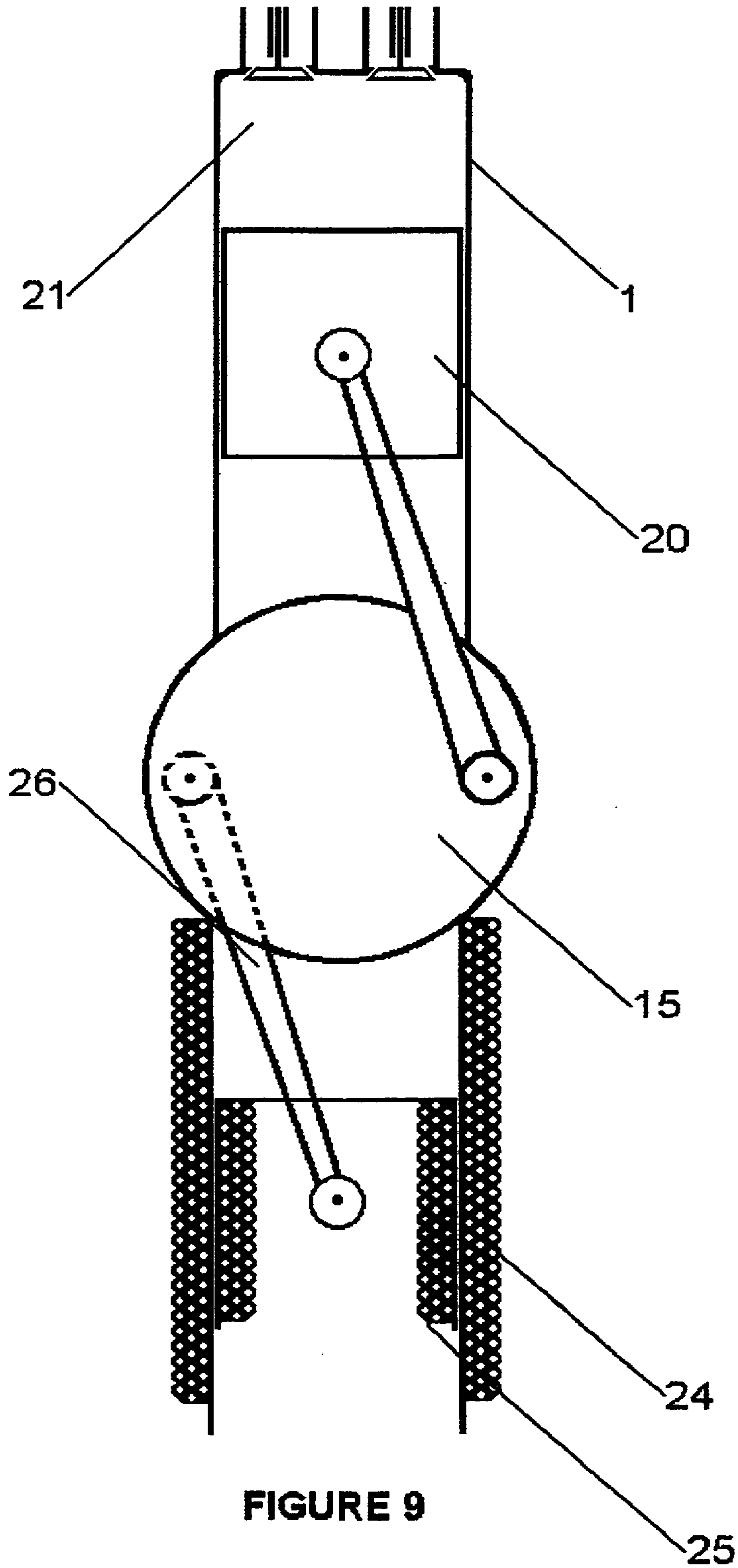

FIGURE 9

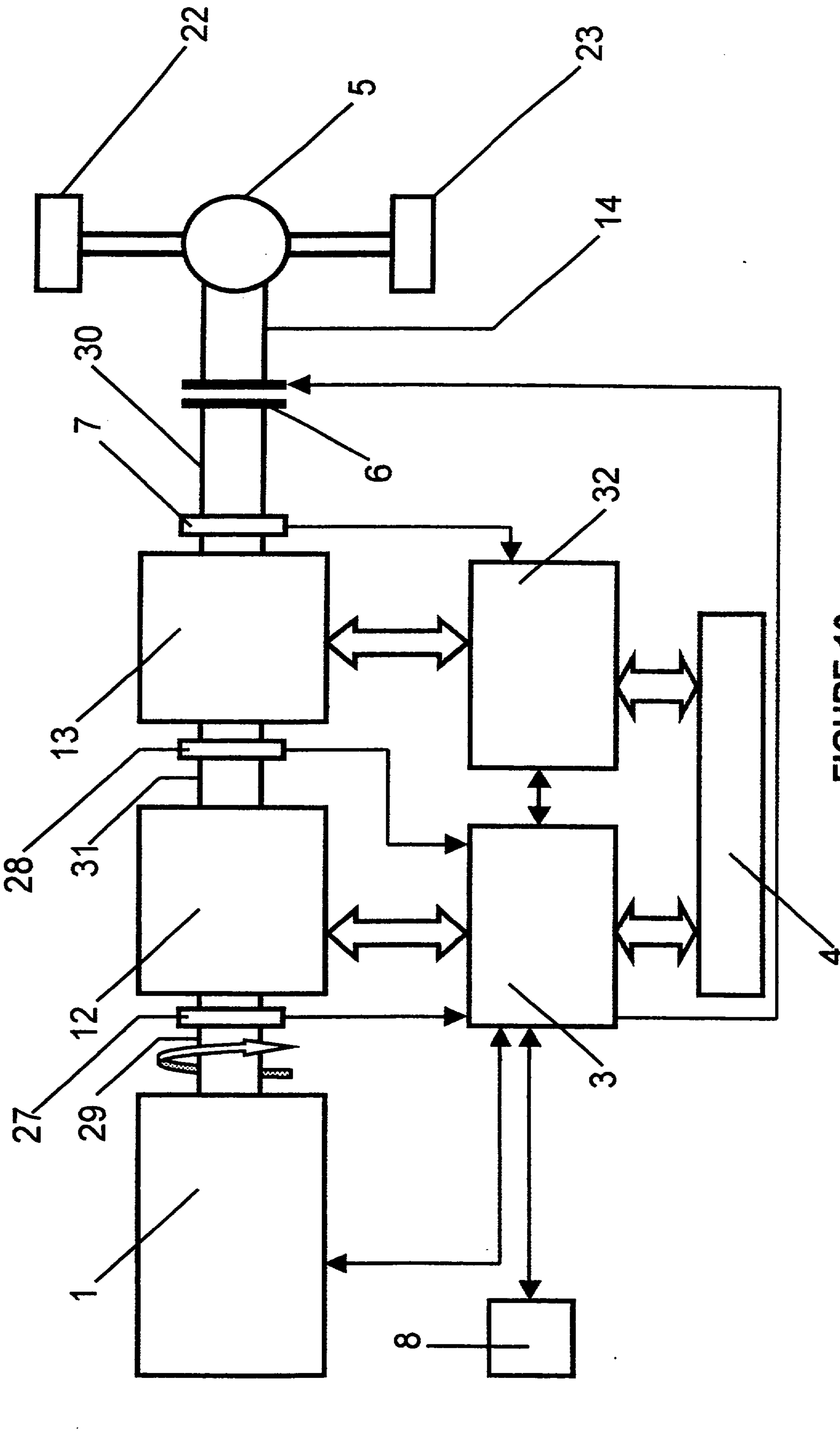

FIGURE 10

VEHICLE HYBRID DRIVE SYSTEM AND OPERATING METHOD

This invention relates to a propulsion system in a hybrid drive arrangement for a motor vehicle which may be propelled simultaneously by an internal combustion engine operating in a regulated cycle mode and by an electrical machine coupled directly to a final drive element.

Patent US 5,873,801 discloses a high efficiency electromagnetic coupling consisting of two electrical machines which are used to form a rigid connection between an engine and an output drive shaft which enables the torque and rotation of the engine to be transmitted to the output drive shaft. It also provides electric power regeneration means arranged on the output shaft of the engine for regenerating electric power via the output shaft, and means arranged on the drive shaft for regenerating electric power via the drive shaft for charging a storage battery.

Patent WO9921263 discloses a combined serial and parallel hybrid drive wherein an additional electric motor is connected through a clutch arrangement between the output of the thermal engine and the electrical machine combination, and the gearbox driving the wheels of the vehicle. Both the electrical machine (motor/generator) and the electric motor can be driven by the thermal engine to charge an electric accumulator and can receive power therefrom to provide extra torque to the output shaft.

Patent US 5,714,851 discloses a serial hybrid drive which by means of an arrangement of a bypass line and of a switching element, energy generated by the internal combustion engine (and converted in the generator) can be supplied to the driving motor in either of two ways: via the rectifier-DC line-inverter path on the one hand, or directly by way of the bypass line on the other. The former method of operation is particularly suitable for situations with a highly fluctuating drive load because the inverter can be used to control the dynamics. In situations with a more constant drive load, however, a switch-over may take place to the bypass line, whereby energy is conducted directly from the generator to the driving motor, thereby avoiding losses in the rectifier, inverter and the DC line, and achieving improved driving efficiency.

Patent document DE 198 14 402 discloses hybrid drives in which the internal combustion engine is directly coupled to an electrical machine which serves as a drive motor to provide the initial acceleration to the stationary motor vehicle and for starting the internal combustion engine. The electrical machine also can function as a generator to replenish the electrical energy used during the starting cycle. Smooth transition between propulsion by the electrical machine and the internal combustion engine may be achieved by two alternative methods. Firstly, by decoupling the internal combustion engine and starting it separately and then synchronising its shaft speed with the electrical machine prior to engaging a clutch. Secondly, by rotating the internal combustion engine without compression, for example, through the use of valves capable of being controlled electronically typically by electro-magnetic actuation, until a pre-set speed is achieved. A process of valve synchronisation, fuel injection and ignition then starts the internal combustion engine which provides power for the drive system.

In such conventional hybrid drive systems, the free running characteristic of internal combustion or thermal engines, which have poor low speed torque characteristics, is utilised. An object of the present invention is to provide a hybrid drive of the type mentioned above which has an internal combustion or thermal engine, an electrical machine and an energy accumulator, but in which the internal combustion or thermal engine contributes energy to all parts of the acceleration and speed cycles, and whose method of operation can be adapted to different drive requirements including motor cycles, ships and railway locomotion. Another objective is to provide step-less operation from start to maximum speed with improved acceleration characteristics. Another objective is to reduce the size and weight of the electrical machine and stored energy requirements through the contribution of the internal combustion engine. Another objective is to minimise transmission slippage and power losses through the provision of a direct drive arrangement. Another objective is to reduce harmful exhaust emissions during acceleration cycles, slow speed and stationary operation. Another objective is reduce wear in the internal combustion engine during cold starts when about 70% wear normally occurs. Another objective is to improve energy utilisation and efficiency due to the recovery of energy during the internal combustion engine's power cycle at all speeds and from the vehicle's momentum during braking. These and other objects, advantages and features are advantageously accomplished the hybrid drive arrangement and operating method

according to the present invention in which the operational cycles of the internal combustion engine are actively controlled by an electrical machine such that the combined system output provides high torque at low speeds suitable for direct drive with low transmission losses.

According to the present invention in a first embodiment there is provided an internal combustion engine coupled directly to an electrical machine, a power control unit, a speed and torque sensor, an electrical energy accumulator, a clutch and a final mechanical drive.

The control strategy adopted to control the drive system is a two-stage combination of feed-forward and feedback adaptive control techniques. In the feed-forward stage, predicted values are calculated from tables of performance of the internal combustion engine and electrical machine, and compensating algorithms applied according to factors including temperature, air pressure and the calorific value of the fuel. In the feed-back stage of control, the values of torque and speed achieved are measured repeatedly at regular time intervals on the required acceleration or speed profile and the necessary adjustments re-calculated. This adaptive form of control is implemented with high-speed computers and software familiar to those skilled in the art.

When a input specifying a particular speed is received by the power control unit from the manual input control unit, an acceleration profile is calculated given the level of available energy stored in the energy accumulator and the predicted energy that can be generated by the internal combustion engine. The proportions of power contribution which the internal combustion engine and electrical machine will each contribute to achieve the desired speed is calculated together with the amounts of fuel necessary to be injected in successive cycles and the required field (stator) and armature (rotor) currents.

The electrical machine is energised as a motor to provide starting torque for the drive. During the initial rotation of the drive shaft, the inlet and exhaust valves (where fitted) of the internal combustion engine are synchronised to prevent compression. At the start of the first full cycle of the internal combustion engine, a compression cycle (full or partial) is initiated and a measured amount of fuel is injected into it. Up to this stage the internal combustion engine is a net consumer of

energy, but during its power cycle it momentarily generates energy. When this occurs, the energisation of the electrical machine is changed so that it operates in its generation mode and provides a negative torque (or load) which constrains the output speed of the internal combustion engine. To achieve this, the field and armature currents of the electrical machine are continuously varied to compensate for the non-linear torque pulse characteristics produced by the internal combustion engine and this energy is extracted and fed to the energy store and to the final drive. In this way, a smooth combined torque output characteristic is produced. This process continues until the desired speed is reached when, under normal operating circumstances, the internal combustion engine will be a net contributor of energy. During deceleration, the vehicle's momentum is recovered and converted into electrical energy through the technique of regenerative braking and stored. Where applicable or necessary, dynamic and plug braking can also be used for supplementary control of the internal combustion engine, low speed braking or emergency braking.

The key factor in the overall energy management in this system is that the relationship between power and time is such that high demands for power usually only occur during transitions that are have short duration or during sustained high speeds. Transitional energy demands may be categorised into acceleration related requirements that last for a few seconds and climbing gradients which last for a few minutes. In both cases, energy in the electrical energy storage unit is temporarily reduced, but the system is proportioned so that under steady-state conditions there will be a net contribution of energy available from the internal combustion engine to replenish the electrical energy storage unit. If the desired speed is very slow and prolonged, which are conditions typically encountered in traffic crawls, the acceleration energy demands are also low. Under these circumstances, the internal combustion engine may still be a net contributor of energy, but the energy store will be depleted especially if ancillaries such as air conditioning and lights are required. The main effect of the depletion of the energy store is to reduce the acceleration capacity of the system. If the energy store levels should fall to very low levels, the energy management control shuts down non-essential loads and provides a warning that the drive system needs recharging. This can be achieved when stationary by disengaging the clutch so that the internal combustion engine can be used to replenish the energy store.

According to the present invention in a second embodiment there is provided an internal combustion engine coupled directly to two electrical machines, two power control units, a speed and torque sensor, an electrical energy accumulator, a clutch and a final mechanical drive. The operation of this system is the same as the previous embodiment in its essentials with the exception that two rigidly coupled electrical machines on the same shaft are provided. One operates at a low frequency primarily for the propulsion or traction requirements. The second electrical machine operates at high frequency primarily as a rapid response for derivative control of high rates of change of torque due to the compression and power cycles of the internal combustion engine. This permits optimisation of the magnetic design of one electrical machine and power control for generation or motoring to operate with low frequency control, while the other can operate optimally with high frequency control.

These and other objects, features, aspects, and advantages of the present invention will become more apparent from the following detailed description of the preferred embodiments of the invention when considered with the accompanying drawings.

The first embodiment of the invention will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

Figure 2 schematically illustrates the electronic power switching arrangement of part of the power control module for a rotary DC separately excited electrical machine

Figure 3 is a graph showing the typical torque characteristics of a one complete operation cycle of a four-stroke internal combustion engine

Figure 4 is a graph showing the torque contribution of the electrical machine during one complete operation cycle of a four-stroke internal combustion engine, and the combined resultant output torque of the hybrid drive system

Figure 5 is a graph illustrating speed and acceleration for a typical short cycle operation of a vehicle

Figure 6 is a graph showing the relationship between the average power provided by the electrical energy storage unit and the total energy utilisation

Figure 7 is a cross-section of one cylinder of an internal combustion engine

Referring to Figure 1, it will be appreciated that the hybrid drive illustrated is particularly suitable for driving a motor vehicle. It is constructed with an electrical machine 2, which is a separately excited DC electrical machine and is mechanically coupled to an internal combustion engine 1 by way of a drive shaft 29. The internal combustion engine 1 in this embodiment and shown schematically in Figure 7 it operates with four-strokes, has spark ignition 19, direct injection 18, electronically controlled inlet valve 16 and exhaust valve 17 (with vacuum or electromagnetic actuation), single or multiple cylinders and combustion chambers 21 and a petrol energy source. Referring to Figure 2, a four-lead line connects the field winding 9 and the armature winding 10 of an electrical machine 2 to a power control unit 3 which is connected to an electrical storage unit 4. The electrical storage unit 4 is able to accept, deliver and store large quantities of electrical energy in short time periods by means including capacitive, inductive and battery devices whose implementation can be carried out by a person skilled in the art. Referring to Figure 1, the input of energy to an electrical machine 2 and output of energy from an electrical machine 2 is controlled by a power control unit 3 and mechanically transmitted by a drive shafts 30 and 14. The drive shaft 14 is connected to a clutch 6 and a final mechanical drive differential gearbox 5 which is connected to wheels 22 and 23 for propulsion. The clutch 6 decouples drive shaft 14 when the vehicle is stationary and ancillary equipment or electrical storage unit requires energy to be replenished.

Figure 5 shows a typical operating cycle in which a vehicle is accelerated from rest in time 0-t_1, maintains a speed for a time t_1-t_2, accelerates to a higher speed in time t_2-t_3, maintains a speed for a time t_3-t_4, and decelerates to rest in a time t_4-t_5. Figure 6 shows schematically the average energy provided by the electrical machine 2 corresponding with the vehicle duty cycle indicated in Figure 5. During the period acceleration 0-t_1, the average power is positive (+ve) and the electrical machine operates mainly as a motor; during the concstant speed period t_1-t_2, the average power is negative (-ve) and the electrical machine operates mainly as a generator

with the internal combustion engine 1 providing a net input of energy into the system; during the acceleration period t_2-t_3, the average power is positive (+ve) and the electrical machine operates mainly as a motor to assist with the acceleration demand; during the constant speed period t_3-t_4, the average power is negative (-ve) and the electrical machine operates mainly as a generator with the internal combustion engine 1 providing a net input of energy into the system; during the deceleration period t_4-t_5, the average power is negative (-ve) and the electrical machine operates mainly as a generator with the momentum of the vehicle providing a net input of energy through regeneration into the system for energy storage. To control the individually illustrated hybrid driving components for the purpose of implementing the described different modes of operation and functions, a corresponding power control unit 3 is provided, whose implementation can be carried out by a person skilled in the art, as can the various modifications of the above-described hybrid drive within the scope of the invention. Thus, the use of the hybrid drive is not limited to motor vehicles but may also be considered wherever an element is to be mechanically driven by means of a hybrid drive. It is also understood that, when the hybrid drive is used in a motor vehicle, not only the two wheels 22 and 23 shown with the final differential drive 5 as an example, but at least also a possibly existing single wheel or multiple driving wheels can be driven by the hybrid drive system, in which case, for example, instead of the one illustrated hybrid drive system, a separate hybrid drive system may be provided for each wheel. These hybrid drive systems may be connected and synchronised in parallel.

The power control unit 3 receives various sensor information from an internal combustion engine 1 including valve positions, engine coolant temperature, rotational angle of the crankshaft, air pressure, intake air volume and temperature, oxygen level, and carbon monoxide level. It sends control signals that include valve operation, fuel injection, and spark ignition to the internal combustion engine. The power control unit 3 also receives information concerning torque and speed from sensors 7 and 27 and from a manual input control unit 8 which controls the set or desired speed, acceleration, direction of rotation, control of a final drive clutch 6 and provides system status indications. The detailed description now proceeds with the function of the internal combustion engine.

Referring to Figures 1, 3, 4 and 7, at the start of the operation of the drive system, the power control unit 3 energises an electrical machine 2 so that it rotates a

crankshaft 15 of an internal combustion engine 1 and opens an electronically controlled inlet valve 16 and exhaust valve 17 such that the compression of air in a combustion chamber 21 is prevented. When a piston 20 approaches top dead centre (TDC), the command to close both the valves is given to avoid contact with the top of the piston. At the beginning of the intake (down) stroke (0° - 180° in Figure 3), inlet valve 16 is opened and air is drawn into a combustion chamber 21. The inlet valve 16 opening can also be modulated so that variable amounts of air can be drawn into a combustion chamber 21. This part of the cycle requires an energy contribution from an electrical machine 2 (shown as positive torque in Figure 4) and an energy absorption in the internal combustion engine 1 (shown as negative torque in Figure 3).

During the compression cycle (180° - 360° in Figure 3), inlet valve 16 is normally closed at bottom dead centre (BDC) and fuel is injected into the combustion chamber by an injector valve 18 to achieve an optimum air/fuel ratio (typically 14.7:1 for minimum exhaust emission). Variable compression ratios can be achieved through modulation of an exhaust valve 17. The torque contribution by the electrical machine increases as the piston 20 travels towards the top of the combustion chamber 21, and causes the compressed gas to exert its greatest pressure when it reaches TDC.

In the power cycle (360° - 540° in Figure 3), the fuel/air mixture is ignited by a spark ignitor 18 and the resulting explosive reaction causes linear motion of a piston 20 pressed down by the explosion of the air/fuel mixture to be converted into rotational motion by a crankshaft 15. The first part of this power stroke results in an energy release which is shown as a positive torque contribution in Figure 3. The expansion of the gases continues to transfer energy represented by positive torque until an exhaust valve 17 is opened towards the end of the power cycle. As soon as this occurs, the engine begins to require energy to complete the final exhaust cycle (540° - 720° in Figure 3) and is shown as negative torque.

Simultaneously with the operation of the internal combustion engine 1, an electrical machine 2 compensates for the irregular shaped torque pulses and provides a smooth output to the final mechanical drive 5. Figure 4 shows the torque contribution of the electrical machine as a 'mirror image' of that required by the internal combustion engine. During the intake and compression cycles (0° - 360° in

Figure 4), the electrical machine is required to operate as a motor and it provides torque to both the internal combustion engine 1 and to the final drive 5 to move the vehicle. The power for this is drawn from an electrical storage unit 4 and the resultant torque is shown in Figure 4 as the 'output torque' on the graph. In the intake, compression and exhaust cycles shown, the system is a net consumer of electrical energy, and during the power cycle the internal combustion engine 1 contributes energy proportional to the area under its torque curve. During a short period in the power cycle of the internal combustion engine 1 the resultant torque of the electrical machine 2 is shown as negative. This occurs when the internal combustion engine becomes a net producer of energy and surplus energy may be stored in the electrical storage unit 4.

The electrical machine is required to operate as a generator during the power cycle of an internal combustion engine, and exerts a retardation effect on the crankshaft 15 of the internal combustion engine 1 through the drive shaft 29 in Figure 1 of the drive system. Energy transmitted through output shafts 30 and 14 and not absorbed by the final drive 5 is returned to an electrical energy store 4 or absorbed in the windings of the electrical machine 2. In its effect, the action of the electrical machine enables the power release of the power cycle of the internal combustion engine to be distributed over all the operational cycles (0° - 720°) of the engine by storing energy electrically. This process of active power cycle averaging, through the operation of the electrical machine electrical energy store, is analogous with a variable mass flywheel which permits fast acceleration (low mass), but yet smoothes power cycle torque pulses and facilitates very low speed operation (high mass). The detailed description continues with the function and operation of the electrical machine.

Referring to Figure 2, the schematic indicates eight high speed electronic switches (S1 - S8) arranged as two full bridges controlling a field 9 (or stator) and an armature 10 (or rotor) of an electrical machine 2. The two full bridges each consisting of four high speed electronic switches provide four quadrant operation with facility for regeneration, dynamic (rheostatic) braking and plug braking for an electrical machine. The high speed switches can be constructed by devices including IGBT's, MOSFET's and GTO thyristors depending on the power and frequency requirements of the drive system. The high speed electronic switches are controlled by a central processing unit 11 which contains all the necessary data,

operational models and software programmes (not shown), receives voltage and current sensor inputs from the field (stator) 9 and armature (rotor) 10 of the electrical machine 2, and connects to other parts of the power control module associated with the internal combustion engine management systems (not shown).

During the intake cycle of the internal combustion engine 1 the electrical machine 2 operates in its forward motor mode and provides power to the final drive 5 and for the intake cycle. The field (stator) winding 9 is energised when S1 and S4 are closed and S2 and S3 are open. The field current is varied according to the principle of pulse width modulation (PWM) when S4 is opened and closed alternately with S1 closed. Due to the inductance of the field winding 9, a decaying current continues to flow in a path provided by D3 and S1 when S4 is opened and is maintained by the collapsing magnetic field of the field winding (flux decay). In the same way, the current in the armature winding 10 is controlled by S5 and S8. When S5 and S8 are closed together, the supply voltage appears across the armature terminals and its current rises. When S5 is opened and S8 remains closed, the armature current circulates and decays through S8 and D6 during forward motoring.

During the compression cycle, the torque requirement of the internal combustion engine increases rapidly until TDC is reached. As soon as the power cycle begins and ignition has occurred, there is a very rapid change in torque polarity due to the explosive combustion reaction. The derivative nature of these high rates of change of torque requires that an unconventional approach to maintaining control stability of the drive system during these transition phases is adopted.

During these transition phases, the field is modulated by reversing its flux which reduces undamped oscillations, the machine's response times and improves stability. During this mode of operation, S1 and S4 close simultaneously while S2 and S3 are opened which provides positive energisation of the field 9 ($+I_F$). Negative energisation of the field 9 occurs when S1 and S4 are open and S2 and S3 are closed ($-I_F$). The ratio of open to closed times is regulated according to the principle of pulse width modulation so that the resultant of the applied current at a duty cycle of 0.5, for example, is zero ie. $+I_F = -I_F$. By modulating the field in this way, the rotor is alternately accelerated and retarded so that, at a duty cycle of 0.5, the rotor is electromagnetically locked by equal and opposite torques being exerted on it by the field. The intensity or level of this counter-balancing torque is varied by the

armature current according to the torque equation $T=k.I_F.I_A$. At other duty cycles, the resultant positive or negative field current provides a forward or reverse direction of rotation of the electrical machine. Although there is a power penalty for this mode of control, it is mitigated by only using it for a very short time during the compression and power cycles of the internal combustion engine. Alternatively, the armature current can be reversed and modulated in the same way as the field current described above. A further control strategy is to modulate both armature and field currents simultaneously.

When high rates of increasing torque are required in the compression cycle of the internal combustion engine, the additional torque is provided by switching from the conventional field flux decay mode of control to the field reversal mode of control in the bridge (S1 - S4). This is achieved by increasing the positive current pulses while introducing short negative current pulses to prevent instability in the desired torque output. When the power cycle is initiated by the ignition of the fuel/air mixture, the field of the electical machine is modulated so that its rotor is momentarily locked by the opposite torques exerted on the drive shaft by the field current. The electrical machine then controls the release of the energy generated by the internal combustion engine by controlling the movement of a drive shaft 29. The control processing unit 11 determines the levels of current necessary to maintain the required speed (or acceleration) and is dependent of the resultant torque applied to the final drive which is the difference between the sensors 27 and 7. Initially, the movement is controlled by net field reversal which has a similar effect as plugging an electric motor. Later in the cycle, regeneration and storage of energy, surplus to the immediate requirements of the hybrid drive system, occurs.

Energy recovery of the power cycle of an internal combustion engine through regeneration of electrical energy to the electrical storage unit 4 is provided by an armature circuit 10 with eternal excitiation provided by a field winding 9. During motoring (and plugging), the armature current is controlled by switches S5 and S8. The armature (rotor) 10 is energised when S5 and S8 are closed. The current is varied according to the principle of pulse width modulation (PWM) when S8 is opened and closed alternately. Due to the inductance of the armature 10, a decaying current continues to flow in a path provided by D6 and S8 when S5 is opened and is maintained by the collapsing magnetic field of the armature (flux decay). During generation, S5, S7 and S8 are opened. When S6 is closed, the

armature current rises and flows through S6 and D8. When S6 is opened, the electrical machine acts as a generator and returns energy to the electrical storage unit 4 through D8 and D5; it also produces a counter torque on the drive shaft 14. Generation stability is maintained through control of the field winding 9. After completion of the power cycle of the internal combustion engine, the electrical machine reverts to its motoring mode of operation and provides torque for the exhaust cycle and final drive.

Energy may also be recovered through regeneration during braking of the vehicle. In this case, the internal combustion engine does not contribute energy since the inlet and exhaust valves are synchronised so that no compression is produced, no spark ignition is provided and no fuel is injected. All the energy from the momentum of the vehicle is usually recovered electrically unless the electrical storage unit cannot accept energy, and energy may then be dissipated dynamically in the electrical machine or mechanically using compression cycles in the internal combustion engine for retardation. When the hybrid drive system is operated in reverse, the internal combustion engine is not used for power generation and its inlet and exhaust valves are synchronised so that no compression is produced, no spark ignition is provided and no fuel is injected.

Referring to Figure 1, a clutch 6 arrangement between the final drive 5, final drive shaft, and output shaft 30 of the hybrid drive system is also provided to decouple the electrical machine 2 and internal combustion engine 1 from the final drive 5. This facility is used when ancillary equipment including air-conditioning and heating systems need to be powered while the vehicle is stationary, or when the energy storage unit 4 has become depleted. It is actuated by the power control unit 3. The clutch 6 may be omitted in applications which do not require this facility such as motor cycles or where multiple hybrid drives are interconnected.

The second embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 10 shows by a schematic block diagram the general arrangement of the hybrid drive system with two rotary electrical machines.

Referring to Figure 10, the second embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements have been heretofore described. In this configuration, two electrical machines 12 and 13 with their associated power control units 3 and 32, speed and torque sensors 28 and 7 and output shafts 31 and 30 are included. The first electrical machine 13 operates with low frequency power control to provide a control response appropriate for propulsion (or traction). The second electrical machine 12 operates with high frequency power control to provide fast response to high rates of change of torque associated with control of the output of the internal combustion engine 1. Both electrical machines operate simultaneously and in series being coupled together by drive shaft 31, with a combined output which addresses the torque power spectral density characteristics of the internal combustion engine 1 and load transmitted by the final drive 5. Electrical machine 13 is designed and adapted to respond to low frequency components and electrical machine 12 designed and adapted to respond to high frequency components of the power density spectrum.

The third embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

Figure 8 shows by way of a schematic diagram the general arrangement of an electrical machine configured with linear windings integrated with an internal combustion engine

Figure 9 shows by way of a schematic diagram the general arrangement of an electrical machine configured with linear windings mounted remotely from an internal combustion engine

The third embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the windings of electrical machine are distributed to produce linear motion rather than rotational motion. Referring to Figures 1 and 8, the stator 24 of the electrical machine is located about

one or more combustion chambers 21 of the internal combustion engine 1, and the linear actuator 25 is located in one or more pistons 20. The windings of the electrical machine are so disposed as to produce electromagnetic fields providing positive displacement along the axis of the movement of the piston 20, resulting in either retardation or acceleration forces to be exerted on the crankshaft 15 according to the impressed currents conveyed by the power control unit 3. Alternatively, referring to Figure 9, the windings of the electrical machine may be mounted remotely from the combustion chamber 21 of the internal combustion engine 1, and in communication with and acting upon a common crankshaft 15 by positive linear displacement through a connecting rod 26, and thereby permitting acceleration or retardation forces to be caused upon said crankshaft.

The fourth embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

The fourth embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the internal combustion engine 1 operates with four-strokes and compression ignition with single or multiple cylinders.

The fifth embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

The fifth embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the internal combustion engine 1 operates with two-strokes and compression ignition or, alternatively with spark ignition, and with single or multiple cylinders.

The sixth embodiment of the invention will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

The sixth embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the internal combustion engine 1 operates with a rotary rather than reciprocating action, or alternatively, as a gas turbine.

The seventh embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

The seventh embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the electrical machine 2 is a rotary or linear AC synchronous machine.

The eighth embodiment of the invention will now be described by way of example with reference to the accompanying drawing in which:-

Figure 1 shows by a schematic block diagram the general arrangement of the hybrid drive with a single electrical machine

The eighth embodiment of the invention operates substantially as the first embodiment inasmuch as the means and various components and elements are heretofore described, whereas in this configuration the electrical machine 2 is a rotary or linear, AC asynchronous machine.

The internal combustion engine driven by means of petrol is used as the engine 1 in the above hybrid drive system is used by way of example. The principle of the

invention is, however, applicable to other internal combustion engines and external combustion engines, such as Diesel engines, Wankel engines, turbine engines, and jet engines. Other electrical machines such as permanent magnet (PM)-type synchronous motors variable reluctance (VR)-type synchronous motors, vernier motors, induction motors, super-conducting motors, and stepping motors may be used. The brushes used as means for transmitting electric power to the rotor (or linear actuator) of the electrical machine may be replaced by a rotary transformer, a slip ring-brush contact, a slip ring-mercury contact, a semiconductor coupling of magnetic energy, or the like. The energy storage unit 4 may include lead-acid cells, NiMH cells, Li cells, or the like cells. Although the hybrid drive system is mounted on a vehicle in the above embodiments, it may be mounted on other transportation means like ships and aeroplanes as well as a variety of industrial machines.

While the invention has been described and illustrated in several forms, it is to be clearly understood that the same is by way of illustration and example, and it will be obvious to those skilled in the art that the invention is not so limited nor is it to be taken by way of limitation, but is susceptible of various changes and modifications without departing from the spirit thereof.

CLAIMS

1. A vehicle hybrid drive system and operating method comprising an internal combustion engine; a power control unit; an electrical energy accumulator; and an electrical machine coupled directly to said internal combustion engine, whereby said electrical machine is controlled by said power control unit to operate alternately as a generator to retard said internal combustion engine, and as a motor to assist said internal combustion engine, and thereby regulate the operational cycles of said internal combustion engine.

2. A vehicle hybrid drive system and operating method as claimed in Claim 1 wherein energy is extracted during each power cycle of said internal combustion engine by said electrical machine and conveyed electrically by said power control unit to said electrical energy accumulator for storage therein.

3. A vehicle hybrid drive system and operating method as claimed in Claims 1 and 2 further comprising a final mechanical drive and drive shaft coupled directly to said electrical machine wherein energy is extracted during each power cycle of said internal combustion engine by said electrical machine and is conveyed either mechanically to said final mechanical drive by means of said drive shaft for propulsive effort, or electrically by said power control unit to said electrical energy accumulator for storage therein.

4. A vehicle hybrid drive system and operating method as claimed in Claims 1-3 wherein said electrical machine provides torque for propulsive effort to said final mechanical drive and drive shaft with energy provided by said electrical energy accumulator through said power control unit.

5. A vehicle hybrid drive system and operating method as claimed in Claims 1-4, further comprising a wheel or wheels wherein said final mechanical drive is connected as means for propulsion.

6. A vehicle hybrid drive system and operating method as claimed in Claims 1-5, further comprising means to measure speed and torque whereby said

power control control unit regulates the combined speed and torque output of said electrical machine and said internal combustion engine.

7. A vehicle hybrid drive system and operating method as claimed in Claims 1-6 further comprising a manual input control unit wherein an acceleration profile, deceleration profile or speed is calculated by said power control unit according to the level of available energy stored in the electrical energy accumulator and vehicle momentum; and, according to the predicted energy that can be generated by the internal combustion engine, determine the proportions of energy contribution that the internal combustion engine and electrical machine will each contribute to achieve the desired output; and determine the amounts of fuel necessary to be injected in successive cycles of said internal combustion engine, and the required field (stator) and armature (rotor) energisation of said electrical machine.

8. A vehicle hybrid drive system and operating method as claimed in Claims 1-7 further comprising a clutch, wherein said final mechanical drive is decoupled from the output shaft of said electrical machine and said electrical energy accumulator is thereby replenished.

9. A vehicle hybrid drive system and operating method as claimed in Claims 1-8, wherein said electrical machine provides high torque at low speeds from said electrical storage accumulator for vehicle propulsion concurrently with supplementary power from said internal combustion engine for direct transmission to said mechanical final drive.

10. A vehicle hybrid drive system and operating method as claimed in Claims 1-9, wherein said electrical machine provides supplementary acceleration torque for vehicle propulsion from said electrical energy accumulator.

11. A vehicle hybrid drive system and operating method as claimed in Claims 1-10, wherein the electrical machine compensates and smoothes torque pulses produced by said internal combustion engine.

12. A vehicle hybrid drive system and operating method as claimed in Claims 1-11, wherein vehicle propulsion is effected concurrently by said internal

combustion engine operating in a regulated cycle mode, and by said electrical machine operated with energy stored in an energy accumulator.

13. A vehicle hybrid drive system and operating method as claimed in Claims 1-12, wherein said electrical machine provides replenishment of energy in said electrical storage accumulator during propulsion of the vehicle.

14. A vehicle hybrid drive system and operating method as claimed in Claims 1-13, wherein said manual input control unit controls the set or desired speed, acceleration, and direction of rotation of the system.

15. A vehicle hybrid drive system and operating method as claimed in Claims 1-14, wherein a single wheel is driven directly by said electrical machine or combinations of electrical machines.

16. A vehicle hybrid drive system and operating method as claimed in Claims 1-15, wherein multiple driving wheels are driven by multiple separate hybrid drive systems for each wheel which are synchronised for parallel operation.

17. A vehicle hybrid drive system and operating method as claimed in Claims 1-16, said method comprising time related energy management control, wherein transitional energy demands including acceleration which lasts for a few seconds and climbing gradients which lasts for a few minutes, result in temporary depletion of energy in the electrical energy storage unit, which is replenished during periods of steady-state conditions when there is a net contribution of energy available from said internal combustion engine.

18. A vehicle hybrid drive system and operating method as claimed in Claims 1-17 said method further comprising energy management, wherein sustained slow and prolonged speeds and the combined energy requirements of propulsion and ancillaries including air conditioning and lights cause in the depletion of the energy in the electrical energy storage unit, the energy management control shuts down non-essential loads and provides a warning that the drive system needs recharging, which can be achieved when stationary by disengaging the clutch so that the internal combustion engine can be used to replenish the electrical energy store.

19. A vehicle hybrid drive system and operating method as claimed in Claims 1-18 said method further comprising energisation of said electrical machine by modulation of applied current pulses with time, resulting in the production of variable amounts of flux within said electrical machine which may then decay or be reversed to effect control over said internal combustion engine and propulsive effort to said final mechanical drive.

20. A vehicle hybrid drive system and operating method as claimed in Claims 1-19 said method further comprising an adaptive control strategy wherein operating parameters of said electrical machine and said internal combustion engine are stored and compared with measured values of the drive system including speed, torque and currents, together with analysis of the system power spectral densities in order to predict and enact new control parameters.

21. A vehicle hybrid drive system and operating method as claimed in Claims 1-20 further comprising a second electrical machine coupled to said internal combustion engine; a power control unit; and a torque speed sensor, wherein one said electrical machine is operated at low frequency and the other said electrical machine is operated at high frequency, whereby slow and fast regulatory responses and control for both vehicle propulsion and high rates of change of torque produced in said internal combustion engine are effected.

22. A vehicle hybrid drive system and operating method as claimed in Claims 1-21, wherein said electrical machine or combinations of electrical machines are configured with linear windings which are distributed to produce linear motion and integrated with said internal combustion engine, and thereby through positive linear displacement permit acceleration or retardation forces to be caused upon the crankshaft and output of said internal combustion engine.

23. A vehicle hybrid drive system and operating method as claimed in Claims 1-21, wherein said electrical machine or combinations of electrical machines are configured with linear windings which are distributed to produce linear

motion and mounted remotely from said internal combustion engine and in communication with and acting upon a common crankshaft by positive linear displacement through a connecting rod thereby permitting acceleration or retardation forces to be caused upon said crankshaft.

24. A vehicle hybrid drive system and operating method as claimed in Claims 1-23, wherein said electrical machine or combinations of electrical machines are a rotary or linear AC synchronous machines.

25. A vehicle hybrid drive system and operating method as claimed in Claims 1-23, wherein said electrical machine or combinations of electrical machines are rotary or linear, AC asynchronous machines.

26. A vehicle hybrid drive system and operating method as claimed in Claims 1-25, wherein said internal combustion engine operates with four-strokes and compression ignition with single or multiple cylinders.

27. A vehicle hybrid drive system and operating method as claimed in Claims 1-25, wherein said internal combustion engine operates with two-strokes and compression ignition, or alternatively with spark ignition, and with single or multiple cylinders.

28. A vehicle hybrid drive system and operating method as claimed in Claims 1-25, wherein said internal combustion engine operates with a rotary rather than reciprocating action.

29. A vehicle hybrid drive system and operating method as claimed in Claims 1-25, wherein said internal combustion engine operates with a gas turbine engine.

30. A vehicle hybrid drive system and operating method as substantially hereinbefore described, defined and illustrated with reference to Figures 1-10 of the accompanying drawings.

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Application No: GB 0002680.7
Claims searched: 1 to 29

Examiner: Tom Sutherland
Date of search: 27 April 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): B7H (HDE), F1B (BBA)

Int Cl (Ed.7): B60K 41/00

Other: Online: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0743215 A	(TOYOTA) Note column 4 line 14 onwards and the Figs.	X: 1 - 7, 11 to 16, 24 - 27
X	EP 0354790 A	(HITACHI) Whole document relevant.	1, 2, 4, 6, 11, 24 - 27 at least.
X, Y	EP 0175952 A	(MAZDA) See claim 1 and Fig. 3.	1, 2, 4, 6, 11, 24 to 27 at least Y: 22
X	WO 97/08440 A	(CLOUTH) See abstract.	1 - 6, 11 - 16, 24 to 27
X	WO 97/08438 A	(CLOUTH) See Figs and abstract.	1 - 6, 11- 16, 24 - 27
Y	WO 86/04747 A	(TAISHOFF) See the Figs.	22
X	US 5185543	(FICHTEL & SACHS) See claim 1 and Fig. 1.	1 - 6, 11, 24 - 27 at least.

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
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X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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